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Johannes Pernpeintner, and Björn Schiricke



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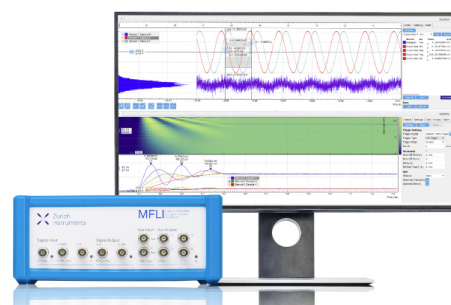
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Parabolic Trough Receiver Heat Loss Measurement – Correction of Absorber Temperature Over-Prediction

Johannes Pernpeintner^{1, a)} and Björn Schiricke^{1, b)}

¹German Aerospace Center DLR e.V., Linder Höhe, 51147 Köln, Germany

^{a)}Corresponding author: johannes.pernpeintner@dlr.de

^{b)}bjoern.schiricke@dlr.de

Abstract. Heat loss testing of parabolic trough receivers with heating cartridge is well-established. In that technique temperature is measured by pressing thermocouples against the inside surface of the absorber tube. As the temperature of the thermocouple is influenced by radiation temperature and air temperature in the annulus, the temperature of the thermocouple is higher than the absorber temperature. The paper presents a measurement of absorber temperature over-prediction as function of heating power between 89 °C and 577 °C for three different insulation configuration yielding over-prediction between 4.4 K and 15.3 K. This shows, that absorber temperature over-prediction is at a relevant order of magnitude for heat loss measurements of parabolic trough receivers. Interpolation using 2nd- and 3rd-order 2d polynomials with the additional condition of disappearing over-prediction at $HL=0$ for correction of heat loss measurements is demonstrated.

INTRODUCTION

Heat loss and optical efficiency of a parabolic trough receiver are essential elements of the efficiency of a parabolic trough solar field. First described by E. Lüpfer et al. [1] heat loss testing was adopted by several laboratories [2], [3], [4], and [5]. Goal of the measurement is to determine heat loss of a parabolic trough receiver as a function of absorber temperature. Results of heat loss testing are used as input parameters for models predicting the yield of a solar field, e.g. using SAM or Greenius, and used as basis for the acquisition decisions of EPCs or collector manufacturers. Hence, test benches for heat loss testing are operated by manufacturers and independent measurement laboratories, often historically connected to research institutes.

The properties of heat loss of the evacuated parabolic trough receiver is dominated by the mechanism that poses the highest heat transfer resistance, which is the radiation heat transfer via the vacuum gap of the annulus between absorber and glass. Hence, the heat loss shows a non-linear behavior reflecting the dependence of radiated power to the forth power of temperature in Stefan-Boltzmann's law.

In a widespread technique of heat loss testing, a central electrical cartridge heater is inserted into the receiver. The ends of the receiver are insulated. About 10 to 12 thermocouples mounted to the heater and bend outwards to touch the inside surface of the absorber and measure absorber temperature. The measurement is evaluated at steady state of quasi-constant absorber temperature and heating power. Assuming adiabatic ends heat loss HL of the receiver is equal to the electrical heating power at that absorber temperature T_{abs} . Several modifications are common: Additional heaters are usually situated under the bellows to account for the inhomogeneity of heat loss at the ends. Furthermore, a homogenization tube from copper or brass can be placed between heater and absorber to homogenize the temperature of the absorber. Finally, counter heaters in the insulation at the ends of the receivers can compensate heat loss via the axial system borders to create adiabatic ends.

While the measurement of electrical power entering the heater cartridge is relatively straight forward using electrical power meters, the measurement of absorber temperature T_{abs} is more difficult: Fig. 1 (a) shows a schematic drawing of the geometry and Fig. 1 (b) shows a photograph of the temperature measurement at DLR: The sheathed thermocouple is situated in the annulus between absorber tube and heater or homogenization tube. In order

to measure the absorber temperature the thermocouple touches the inside surface of the absorber. A spring leave supports the thermocouple to increase the contact force (only shown in Fig. 1 (b)).

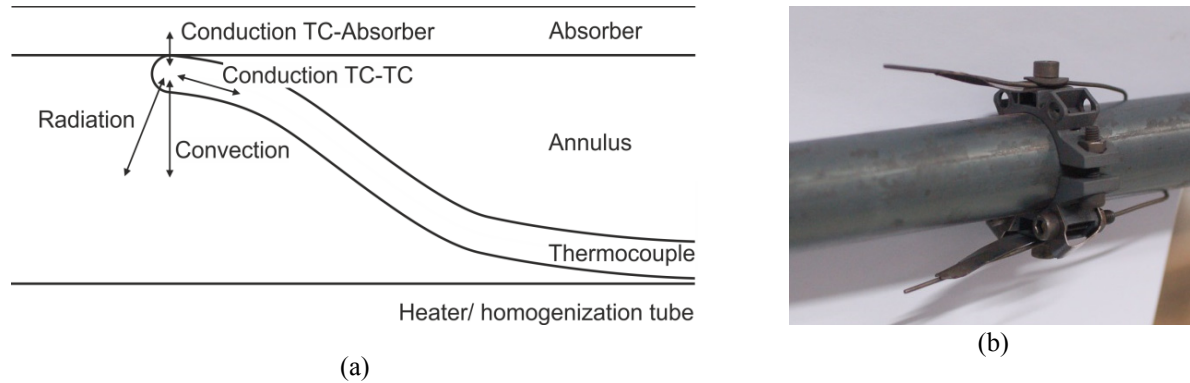


FIGURE 1. Over-prediction of absorber temperature: (a) Heat transfer mechanisms between thermocouple TC and surrounding objects; (b) temperature measurement at the test bench at DLR

The temperature measured using the thermocouple is that of the thermo-electric junction at the tip of the thermocouple. The tip of the thermocouple is connected thermally via the contact point to the absorber which leads to thermal conduction between absorber and thermocouple. Other heat transfer mechanisms influencing the temperature of the tip of the thermocouple are thermal conduction through the thermocouple wire, convection via the air in the annulus between absorber and heater, and radiation heat transfer to annulus surfaces of absorber and heater, compare Fig. 1 (a). The heater is at higher temperature than the absorber as there is a net-flux of energy from heater to absorber. Air- and radiation temperature are also above the temperature of the absorber as they are determined by both absorber and heater. Hence, the tip of the thermocouple acquires a temperature above that of the absorber.

Absorber temperature over-prediction O_p is the difference between the measured absorber temperature $T_{abs,meas}$ and absorber temperature T_{abs} .

$$O_p = T_{abs,meas} - T_{abs} \quad (1)$$

An isothermal absorber is assumed here, as the difference of temperature between inside and outside surface of the absorber can typically be neglected. Using typical thermal conductivities of absorber materials and typical heat loss of parabolic trough receivers it can be shown that for oil receivers the temperature drop from outside to inside surface is typically < 1 K.

Over-prediction can be reduced by optimizing the experimental setup: The influence of radiation temperature on the thermocouple can be reduced with radiation shields under the thermocouple or by covering the surface of the heater/homogenization tube with patches of low-e foils under the thermocouple. Increasing the force used to press the thermocouple at the absorber with spring leaves improves thermal conduction between absorber and thermocouple. However, these means have limits and problems of their own and cannot fundamentally solve the problem: Shields and low-e foils under the thermocouple not only reduce heat transfer from heater/homogenization tube to the thermocouple, but also to the absorber. This introduces cold regions at the absorber at the point, where the absorber temperature is measured. Increasing the force of the thermocouple towards the absorber leads to quicker abrasion and deterioration of the thermocouple, as the thermocouples rub against the absorber when the heater cartridge is inserted and removed from the absorber. Furthermore, even with application of these measures, the question remains: Can absorber temperature over-prediction be neglected? How large is over-prediction?

MEASUREMENT

If over-prediction is measured, then over-prediction can be corrected for. Furthermore the reduction of over-prediction by optimizing of the experimental setup loses importance.

For the measurement of over-prediction thermocouples are attached to the outer surface of a separate absorber without glass envelope, where there is access to the outer surface. The absorber is covered by insulating material

with R-value similar to a normal receiver. Through the additional measurement at the outside surface the over-prediction can be measured, provided, that the temperature measured at the outside can be interpreted as the real absorber temperature. By variation of the temperature and insulation R-value a matrix of measurements can be used than can form a basis for the correction of heat loss measurement. Assuming a correct measurement of absorber temperature at the outside, due to direct accessibility of that thermocouple and connection to the absorber, the over-prediction can be calculated as difference of inner and outer measurement.

In general, over-prediction depends on the concrete properties of the experimental setup of geometry, thermal conductivity, emittance of components and contact forces. A change in the set-up can lead to changes in over-prediction. Hence, changes in the set-up of the heater, aging of the heater, receivers with different diameters, receivers with different absorber materials or surface properties can all lead to differences in over-prediction.

Furthermore, over-prediction depends on both, absorber temperature T_{abs} and heat loss HL . Over-prediction changes with temperature as with changing temperature the relative magnitude of the heat transfer-mechanisms in the annulus shift. While thermal conduction is usually described by linear models, radiation heat transfer depends to the 4th power of temperature. Convection also can show non-linear behavior. Hence, over-prediction will depend on temperature.

Over-prediction will also depend on heat loss HL . Considering two receivers at the same temperature, the receiver with higher heat loss will require a heater at higher temperature, leading to larger temperature gradients in the annulus. Hence, it can be expected that over-prediction will also depend on heat loss.

Burkholder [3,6,7] first demonstrated the measurement of absorber temperature over-prediction and used the data for the correction of heat loss measurements. Burkholder described over-prediction as function of absorber temperature and temperature difference between absorber and heater. As temperature difference between absorber and heater depends on absorber temperature and heat loss, the description is equivalent.

For the measurement presented here thermocouples are soldered to the absorber, compare Fig. 2. In order to achieve the best possible thermal contact, but not increase heat loss locally at the attached thermocouple, the thermocouple is soldered into a groove in the absorber. The advantages of soldering compared to clamping are that soldering does not significantly increase the absorber surface and therefore local heat loss, and that it ensures a thermal contact via the whole surface of the thermocouple.

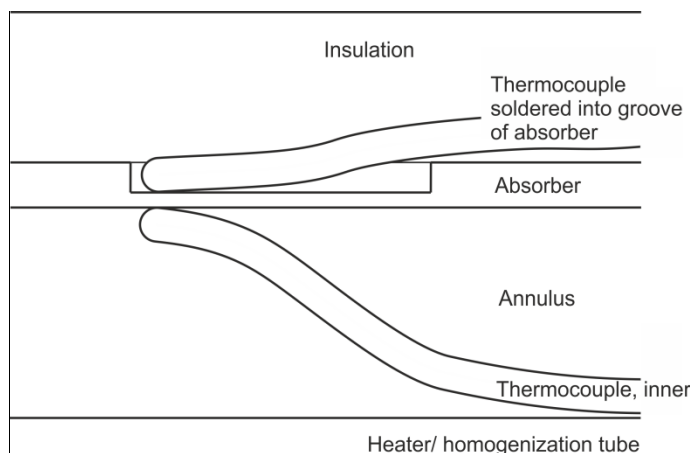


FIGURE 2. Measurement of absorber temperature over-prediction: Thermocouples are soldered to the outer surface of an absorber without glass envelope opposite to the thermocouples of the heat loss measurement; the absorber is covered with thermal insulation

Three types of insulating materials are used: WDS ultra, insulating plates with micro-porosity consisting of inorganic silicates supplied by Porextherm (now: Morgan Advanced Materials plc) offers very low thermal conductivity of with 0.02 to 0.06 W/(m K), depending on temperature. However, WDS ultra is cumbersome to use and breaks easily. Insulating mats supplied by L. & F. Peters GmbH, Isomat 13/120 N-Bio (13 mm), Isomat 13/120 CI – Bio (24 mm), compare Fig. 3 a, are more flexible in application, but offer only moderate insulating power. Aluminum foil, compare Fig. 3 b, allows a clean and non-hazardous application, however the insulation properties are limited.

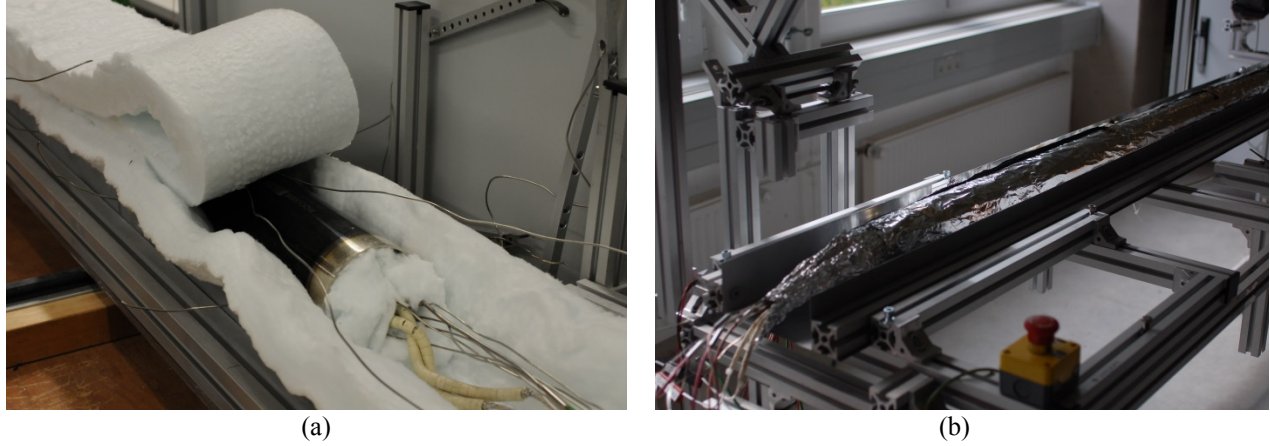


FIGURE 3. Over-prediction of absorber temperature: Heat transfer mechanisms between thermocouple TC and surrounding elements.

Over-prediction is measured at DLR for use in the correction of heat loss measurements. In the following results for a heater for use with absorbers of 70 mm outside diameter and 4060 mm length are presented. At the heater there are 12 thermocouples installed. Six thermocouples are situated at the ends of the absorber, where high homogeneity of the temperature distribution in the insulation is difficult to achieve as translational symmetry is broken. Hence, six thermocouples near the symmetry plane at -1000 mm, 0 mm, + 1000 mm, one facing upwards, one facing downwards are used for measurement. Over-prediction is calculated according to Eq. 1 respectively with the arithmetic mean of the thermocouples at the inside and the outside.

Results are shown in Tab. 1 and Fig. 4. Over-prediction ranges from 4.4 K to 15.3 K. At this order of magnitude the effect cannot be neglected for heat loss measurements and should be corrected for. If the three different insulation configurations are compared, with better insulation and lower heat loss HL over-prediction decreases, which can be expected. More surprising might be the finding that for each insulation configuration, with increasing temperature, over-prediction shows a maximum at temperatures about 250 °C to 300 °C. This might be due to the increased efficiency of radiation heat transfer at higher temperatures.

TABLE 1. Absorber temperature over-prediction O_p measured as function of measured absorber temperature and heat loss HL

Insulation Configuration	$T_{abs,meas}$ in °C	HL in W	O_p in K
1 layer aluminum, 13 mm Isomat	89.3	174.5	9.3
	199.0	515.4	14.7
	301.9	1024.0	15.3
	402.3	1707.5	14.7
	510.0	2595.7	13.8
	574.4	3418.0	13.2
1 layer aluminum, 24 mm Isomat	102.1	122.0	6.1
	198.6	313.9	8.9
	300.6	621.7	9.2
	407.7	1096.1	8.4
	510.2	1698.3	7.4
	573.9	2178.7	6.9
1 layer aluminum, 24 mm Isomat, 13 mm WDS ultra	98.3	89.3	4.4
	201.5	258.2	7.0
	244.5	342.3	7.2
	301.2	478.3	7.1
	402.0	774.0	6.3
	510.6	1222.6	5.5
	577.1	1589.0	5.1

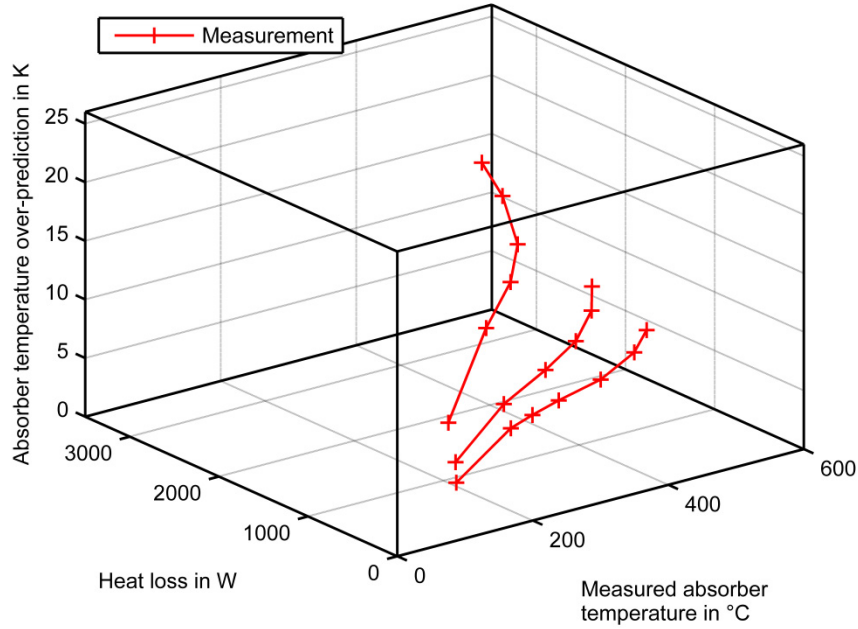


FIGURE 4. Measured over-prediction of absorber temperature as function of heat loss and measured absorber temperature for three insulation configurations.

CORRECTION OF HEAT LOSS MEASUREMENTS

Measurements of absorber temperature over-prediction can be used to correct heat loss measurements provided the set-ups in the annulus are similar in both cases, e.g. in terms of geometry, thermal conductivity, emittance, contact forces, etc.. Result of a heat loss measurement is the pair of measured absorber temperature $T_{abs,meas}$ and associated heat loss HL measured at the same steady state. Hence, the over-prediction of that measurement has to be interpolated using the matrix of measured values.

One method for interpolation is to fit a global fit-function to the matrix of measured over-prediction O_p . In the following 2-dimensional polynomials of 2nd and 3rd order are discussed.

The general 2nd order polynomial for two dimensions, including mixed terms, is

$$y(x_1, x_2) = Ax_1^2 + Bx_1x_2 + Cx_2^2 + Dx_1 + Ex_2 + F \quad (2)$$

where the function $y = O_p$, the variables $x_1 = T_{abs,meas}$ and $x_2 = HL$, and A, B, C, D, E , and F are fitting parameters. However, such a general polynomial should be usable for interpolation, but it has the disadvantage that at the borders of the interpolation region oscillations can occur that make it unsuitable for small extrapolations. One useful modification might be to use additional knowledge about the physics of the system: At a heat loss of zero, which corresponds to perfect insulation, over-prediction must be zero as well, as the temperature differences in the annulus also disappears. If we force the function to contain the line $y(x_1, 0) = 0$, the fit function should yield sensible predictions in the region of small heat loss. Mathematically this means, that in Eq. 2 the terms without x_2 disappear and we obtain the 2nd order polynomial with additional conditions by

$$y(x_1, x_2) = Ax_1^2 + Bx_1x_2 + Cx_2^2. \quad (3)$$

For Eq. 3 fitting parameters are renamed. Fig. 5 shows the fit of the Eq. 3 to the measured data. It can be seen in the graph that $O_p = 0$, if $HL = 0$. Systematic residuals are clearly visible in the fit in Fig. 5. For low temperatures and high temperatures the fit-function is systematically too low, for medium temperatures the fit-function is systematically too high. Hence, a similar analysis is performed for a 3rd order polynomial.

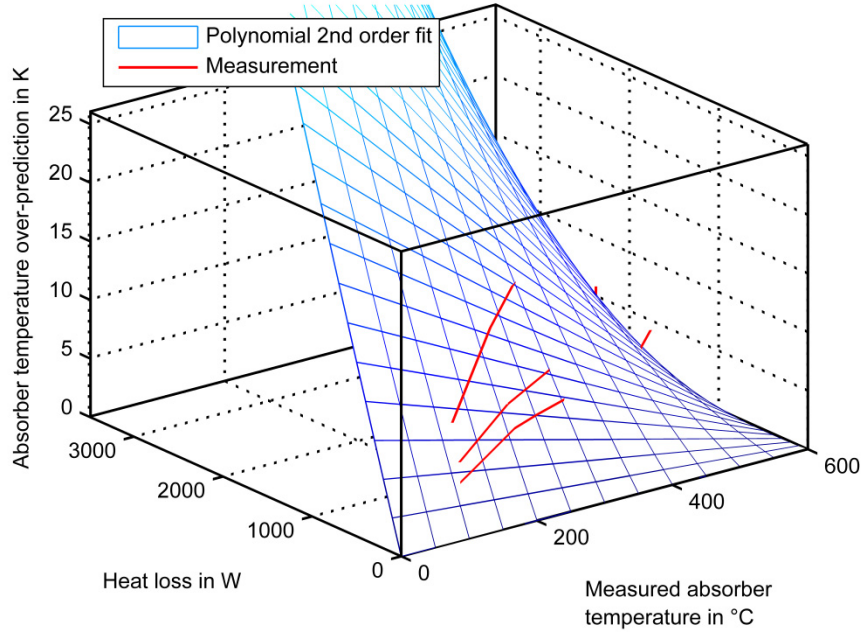


FIGURE 5. Over-prediction of absorber temperature as function of heat loss and measured absorber temperature; measurements and fit of 2nd order 2-dimensional polynomial with additional condition (Eq. 3); best fit parameters $A = 8.13566\text{e-}007 \text{ K/W}^2$, $B = -4.99739\text{e-}005 \text{ K}/(^{\circ}\text{C}^{\circ}\text{W})$, and $C = 2.92941\text{e-}002 \text{ K/W}$. The RMS of the fit is $2.41048\text{e+}000 \text{ K}$.

The general 2-dimensional polynomial of 3rd order with mixed terms is

$$y(x_1, x_2) = Ax_1^3 + Bx_1^2x_2 + Cx_1x_2^2 + Dx_2^3 + Ex_1^2 + Fx_1x_2 + Gx_2^2 + Hx_1 + Ix_2 + J \quad (4)$$

where A, \dots, J , are fitting parameters. Again, assuming $y(x_1, 0) = 0$, the terms without x_2 disappear and we obtain:

$$y(x_1, x_2) = Ax_1^2x_2 + Bx_1x_2^2 + Cx_2^3 + Dx_1x_2 + Ex_2^2 \quad (5)$$

where the fitting parameters are renamed. A fit of the Eq. 5 to the measured data is shown in Fig. 6.

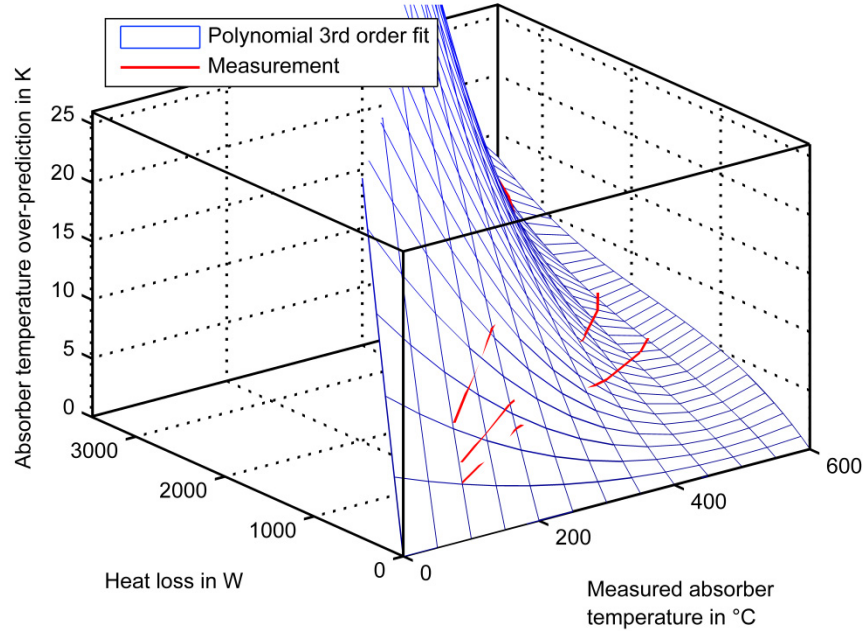


FIGURE 6. Over-prediction of absorber temperature as function of heat loss and measured absorber temperature; measurements and fit of 2-dimensional, 3rd order polynomial with additional condition (Eq. 5); $A = 2.37310\text{e-}007 \text{ K}/(^{\circ}\text{C}^2\cdot\text{W})$, $B = -1.60982\text{e-}008 \text{ K}/(^{\circ}\text{C}\cdot\text{W}^2)$, $C = 5.81315\text{e-}010 \text{ K}/\text{W}^2$, $D = -2.35862\text{e-}004 \text{ K}/(^{\circ}\text{C}\cdot\text{W})$, $E = 6.52070\text{e-}006 \text{ K}/\text{W}^2$, $F = 6.36650\text{e-}002 \text{ K}/\text{W}$, $\text{RMS} = 7.16912\text{e-}001 \text{ K}$

As expected the 3rd order fit reduces residuals, but they still seem systematic. On the other hand, the tendency of polynomials to oscillate becomes apparent at high temperatures. Hence a higher order polynomial is not investigated as oscillations increase with order and the 3rd order polynomial seems to be a reasonable compromise in this case.

Better interpolation might be achieved in the future with fit-functions based on physical models, or 2d spline interpolation.

SUMMARY

As the absorber temperature over-prediction is a systematic effect of a relevant magnitude in the heat loss measurement using central cartridge heater. Over-prediction can be measured and heat loss measurements can be corrected accordingly. In the presented measurements representing a geometry for heat loss measurements of receivers with 70 mm absorber diameter between 89 °C and 577 °C over-prediction was in the range of 4.4 K and 15.3 K. Three insulation configurations were used to enable an interpolation of data. 2d polynomials of 2nd and 3rd order including the additional assumption of disappearing over-prediction at $HL = 0$ were shown to be useful for interpolation. Correction of absorber temperature over-prediction is currently not compulsory in the draft standard developed in IEC TC117.

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